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A New Method to Estimate Cosmological Parameters Using Baryon Fraction of Clusters of Galaxies

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Abstract

We propose a new method to estimate cosmological parameters using the baryon fraction of clusters of galaxies for a range of redshifts. The basic assumption is that the baryon fraction of clusters is constant, which is a reasonable assumption when it is averaged within a Mpc scale. We find that the baryon fraction vs. redshift diagram can estimate the cosmological parameters, since the derived value of the baryon fraction from observations depends on the adopted value of cosmological parameters. We also discuss some points in comparing theoretical calculations with observations.

Key words: Cosmology — Galaxies : clusters of — X-rays

1. Introduction

Clusters of galaxies are the largest virialized systems in the universe and their masses can be estimated by X-ray and optical observations. In general, since there is no efficient way of changing the baryon fraction averaged within a Mpc scale, the baryon fraction of a cluster of galaxies M_b/M_{tot} (M_b and M_{tot} are baryon and total masses of a cluster) should take the global fraction in the universe: Ω_b/Ω_0 (Ω_b and Ω_0 are the baryon density parameter and the total density parameter). White et al. (1993) estimated Ω_0 by identifying M_b/M_{tot} of the Coma cluster with Ω_b/Ω_0 and by using the big bang nucleosynthesis value for Ω_b, and they found that low Ω_0 value is favored: $\Omega_0 = 0.16h^{-1/2}/(1+0.19h^{3/2})$ (where $H_0 = 100h$ km s^{-1} Mpc^{-1} is the Hubble constant). However, in this method, the derived Ω_0 depends on the Hubble constant and studies of the big bang nucleosynthesis. Furthermore, this method does not probe the value of the cosmological constant λ_0.

In this *Letter*, we propose a new method to estimate cosmological parameters (both Ω_0 and λ_0) using the baryon fraction of clusters for a range of redshifts.

2. Cosmological parameter dependence on mass estimation

First of all, we briefly summarize the method to estimate gas, galaxy and total masses of a cluster from X-ray and optical observations paying attention to their cosmological parameter dependence.

Firstly, we describe the gas mass in a cluster of galaxies using X-ray data. For simplicity, we assume that the hot gas in a cluster follows a spherically symmetric isothermal $\beta-$ model (e.g., Sarazin 1988):

$$n_e(r) = n_{e0}\left(1+\frac{r^2}{{r_c}^2}\right)^{-3\beta/2}, \tag{1}$$

where n_e is the electron number density, and n_{e0} and r_c are the central electron density and the core radius, respectively. Then, using X-ray data, the gas mass $M_{gas}(<R)$ within a radius R and the bolometric luminosity $L_X(<R)$ derived by X-ray observation are written as

$$\begin{aligned}
M_{gas}(<R) &= \int_0^R \rho_{gas}(r)4\pi r^2 dr \\
&= \frac{8\pi}{1+X} m_H n_{e0} {r_c}^3 I_M(R/r_c,\beta), && (2)\\
I_M(y,\beta) &\equiv \int_0^y (1+x^2)^{-3\beta/2}x^2 dx, && (3)\\
L_X(<R) &= \int_0^R \left(\frac{2\pi k_B T_e}{3m_e}\right)^{1/2}\left(\frac{2^4 e^6}{3\hbar m_e c^2}\right) \\
&\quad\times[n_e(r)]^2 \bar{g_B}(T_e)\frac{2}{1+X}4\pi r^2 dr \\
&= \left(\frac{2\pi k_B T_e}{3m_e}\right)^{1/2}\left(\frac{2^4 e^6}{3\hbar m_e c^2}\right)\bar{g_B}(T_e) \\
&\quad\times\frac{2}{1+X}4\pi {n_{e0}}^2 {r_c}^3 I_L(R/r_c,\beta), && (4)\\
I_L(y,\beta) &\equiv \int_0^y (1+x^2)^{-3\beta}x^2 dx, && (5)
\end{aligned}$$

where ρ_{gas} is the gas density and other symbols have

their usual meanings. Combining equations (2) and (4) yields the gas mass:

$$M_{gas}(<R) = \left(\frac{3\pi\hbar m_e c^2}{2(1+X)e^6}\right)^{1/2}\left(\frac{3m_e c^2}{2\pi k_B T_e}\right)^{1/4} m_H \times \frac{1}{[\overline{g_B}(T_e)]^{1/2}} {r_c}^{3/2}\left[\frac{I_M(R/r_c,\beta)}{I_L^{1/2}(R/r_c,\beta)}\right][L_X(<R)]^{1/2}. \quad (6)$$

In the above equations, we implicitly assumed that the X-rays are emitted by the thermal bremsstrahlung only (see e.g., Rybicki and Lightman 1979). Note that L_X, r_c and R are not the quantities derived by observations directly, but that they depend on the adopted cosmological parameters. That is, they are estimated as

$$L_X(<R) = 4\pi[D_L(z;\Omega_0,\lambda_0,H_0)]^2 f_X(<\theta), \quad (7)$$

$$r_c = \theta_c D_A(z;\Omega_0,\lambda_0,H_0), \quad (8)$$

$$R = \theta D_A(z;\Omega_0,\lambda_0,H_0), \quad (9)$$

using directly observed quantities: the total bolometric flux $f_X(<\theta)$ within θ, the angular core radius θ_c and the outer angular radius θ (see, e.g., Peebles 1993). In the above equations, D_L and D_A are the luminosity distance and the angular diameter distance which depend on the redshift z of the cluster and cosmological parameters: Ω_0, λ_0 and H_0. Using the relation $D_L = (1+z)^2 D_A$ and paying attention to their cosmological parameter dependences, the gas mass is written as

$$M_{gas}(<\theta) \propto h^{-5/2}\tilde{D_A}^{5/2}(z;\Omega_0,\lambda_0), \quad (10)$$

where $D_A \equiv h^{-1}\tilde{D_A}$. If we estimate the gas mass fixing the value of Ω_0 and λ_0, it is proportional to $h^{-5/2}$, which is a well known relation.

Secondly, we describe the galaxy mass in a cluster. In general, it is estimated as the total blue (absolute) luminosity times the mass-to-luminosity ratio (e.g. White et al. 1993). Note that the total blue luminosity is proportional to ${D_L}^2$ and that the mass-to-luminosity ratio is proportional to h (since it is derived for nearby galaxies, it does not depend on the cosmological parameters except for the Hubble constant). Thus, the galaxy mass M_{gal} in a cluster is written as

$$M_{gal} \propto h^{-1}\tilde{D_A}^2. \quad (11)$$

If we fix the value of Ω_0 and λ_0, M_{gal} is proportional to h^{-1}.

Finally, we estimate the total mass in a cluster of galaxies using X-ray data. We assume that the intracluster gas is in hydrostatic equilibrium. Then, the total mass within the radius R is

$$M_{tot}(<R) = -\frac{k_B T_e R}{G\mu m_H}\frac{d\ln n_e(r)}{d\ln r}\bigg|_{r=R}, \quad (12)$$

thus,

$$M_{tot}(<\theta) \propto h^{-1}\tilde{D_A}. \quad (13)$$

3. Method to estimate cosmological parameters

The basic assumption of our new method to estimate cosmological parameters is that the baryon fraction of clusters of galaxies M_b/M_{tot} is constant. In this method we do not need to assume that M_b/M_{tot} equals the global baryon fraction Ω_b/Ω_0 as in previous works (e.g., White et al. 1993). Based on this assumption, we estimate the cosmological parameters.

Using the results mentioned in the previous section, we can write the baryon fraction ($M_b = M_{gas} + M_{gal}$) in a cluster as

$$\frac{M_b}{M_{tot}} = A\tilde{D_A} + Bh^{-3/2}\tilde{D_A}^{3/2}, \quad (14)$$

where A and B are some cosmological parameter-independent values. In this *Letter*, we concern with only cosmological parameter dependence of the baryon fraction, thus precise formula of A and B is not needed below. In the above equation, the first term comes from the galaxies and the second from the gas. As shown in the above equation, the derived baryon fraction depends on the cosmological parameters through the angular diameter distance.

The basic and plausible assumption adopted in this *Letter* is that the value of M_b/M_{tot} is constant for all clusters. However, the derived value of M_b/M_{tot} depends on the adopted cosmological parameters (Ω_0 and λ_0) in particular at high redshift, since it depends on the angular diameter distance which depends on the adopted cosmological parameters. That is, if we use another cosmological parameters to derive M_b/M_{tot}, we get another value for it. If we adopt the correct values as Ω_0 and λ_0 to estimate mass of a cluster, we obtain the true value of M_b/M_{tot} and it must be constant for all clusters at any redshift. On the other hand, if we adopt incorrect values for Ω_0 and λ_0, we obtain incorrect value of M_b/M_{tot} and it varies with redshift. Thus, we can determine Ω_0 and λ_0 from M_b/M_{tot} as follows: Estimate M_b/M_{tot} for clusters with various redshifts adopting some fixed values as Ω_0 and λ_0 (hereafter M_b/M_{tot} vs. z diagram) . If the derived values of M_b/M_{tot} vary with redshift, then, adopted values of Ω_0 and λ_0 are incorrect. If the derived values of M_b/M_{tot} are constant, then adopted values of Ω_0 and λ_0 are the correct ones.

It is to be noted that derived M_b/M_{tot} depends on Ω_0, λ_0 and h (see eq.(14)). However, the Hubble constant dependence cannot be discriminated unless we know the true value of B in this method. Although uncertainty of the Hubble constant shifts the absolute value of derived

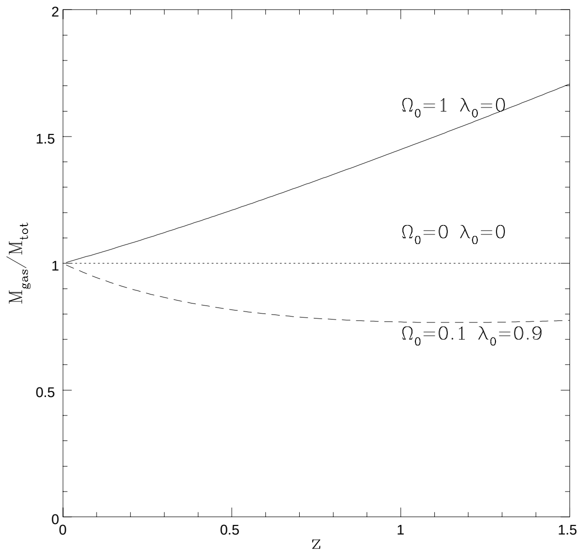

Fig. 1. The expected artificial redshift evolution of the derived M_{gas}/M_{tot}. The values of M_{gas}/M_{tot} are estimated fixing $(\Omega_0, \lambda_0) = (0, 0)$ when the correct values are (1,0) (solid), (0,0) (dotted) and (0.1,0.9) (dotted). Normalization of M_{gas}/M_{tot} is arbitrary.

M_b/M_{tot}, it does not change their behavior of the redshift evolution. Thus, we can determine Ω_0 and λ_0 without knowing the value of h. Furthermore, in the above discussion, we took some assumptions for simplicity, but the final result (eq.(14)) is correct even if we relax some assumptions, for example, the gas is isothermal.

In the following, we study M_{gas}/M_{tot} instead of M_b/M_{tot}, for simplicity. This is justified when the galaxy mass is negligible compared with the gas mass (M_{gal}/M_{gas} is about $20h^{3/2}$ % in the Coma cluster: White et al. 1993) and/or the value of M_{gas}/M_{tot} is constant for all clusters. In this case, we can use more simple way to estimate Ω_0 and λ_0: We estimate M_{gas}/M_{tot} using fixed values of Ω_0 and λ_0. We can predict the artificial redshift evolution of the derived M_{gas}/M_{tot} if the correct values of Ω_0 and λ_0 are different from the adopted values. Thus, we can also determine Ω_0 and λ_0 from derived M_{gas}/M_{tot} (using fixed values of Ω_0 and λ_0) comparing with expected artificial z evolutions. In figure 1, we show the expected artificial redshift evolution of M_{gas}/M_{tot} fixing $(\Omega_0, \lambda_0) = (0, 0)$ when the correct values of (Ω_0, λ_0) are $(1, 0)$, $(0, 0)$ and $(0.1, 0.9)$. Of course, if the correct values of (Ω_0, λ_0) are $(0, 0)$, the derived values of M_{gas}/M_{tot} are constant. On the other hand, if $(\Omega_0, \lambda_0) = (1, 0)((0.1, 0.9))$, then derived M_{gas}/M_{tot} increases (decreases) with redshift. If we can determine M_{gas}/M_{tot} within $\sim \pm 10\%$ for a cluster at $z \sim 0.4$ besides for nearby clusters, we can discriminate three models.

4. Discussion and Conclusions

As mentioned above, the M_{gas}/M_{tot} (or M_b/M_{tot}) vs. z diagram is a potentially useful method to estimate cosmological parameters. However, to estimate them by this method in practice, we need to check some uncertainties. Firstly, the value of M_{gas}/M_{tot} depends on the outer radius of the analysis except for $\beta = 2/3$. Thus, we must know how large a radius is required to derive M_{gas}/M_{tot}. Secondly, we must know whether M_{gas}/M_{tot} (M_b/M_{tot}) is constant or not, in fact. Thirdly, we must know how large a scatter there is. To check these uncertainties, we need first study M_{gas}/M_{tot} (M_b/M_{tot}) for nearby clusters which are not affected by adopted cosmological parameters. Unfortunately at the present, we do not have large samples enough to study this, but in the near future we will be able to have such samples.

At the present, we do not have large samples of M_{gas}/M_{tot} data enough to study its cosmological parameter dependences, in particular at high redshift. Thus, here, we use inhomogeneous samples which are collected from some literatures, to study the possibility of the method mentioned above. It is to be noted that analysis described below using inhomogeneous samples is not conclusive, but illustrative at best. The data are summarized in table 1. In table 1, we assumed $\Omega_0 = 0, \lambda_0 = 0$ and $h = 1$. When the original data are derived using different cosmological parameters, we translate them using the above relation (eq.(14)) to the values for $(\Omega_0, \lambda_0) = (0, 0)$ and $h = 1$. As mentioned above, this data set is inhomogeneous: For example, outer radius of the analysis (see table 1) and method of mass estimation are different for each cluster and literature. In figure 2, we plot M_{gas}/M_{tot} as a function of redshift with expected artificial z evolution curves. In figure 2, the values of data are normalized by the value of the Coma (which is the leftmost one with error bar). Since, here, we are interested in only their redshift evolution and not their absolute values, the normalization is arbitrary. As is seen, there is a large scatter. A part of scatter comes from inhomogeneity of the data set. We think large homogeneous data set will conclude whether this scatter is real or not and how large a scatter there is. If the scatter is real and large, we need some bayon segregation processes for cluster formation and evolution, for example, energy input by galactic winds. Since we think, in general, there is no efficient process of changing the baryon fraction averaged within a Mpc scale, we pay attention to data for which their outer radius is greater than 1Mpc ($\Omega_0 = 0, \lambda_0 = 0$, and $h = 1$) and they are shown as large crosses. The result suggests that high-λ_0 model seems to be disfavored. However, any conclusion must be left until large homogeneous data set is available.

In summary, we proposed a new method to estimate cosmological parameters using the baryon fraction of

Table 1. Data for the baryon fraction.

cluster	redshift	$\frac{M_{gas}}{M_{tot}}(< R)(\%)$	$R(h^{-1}\mathrm{Mpc})$	ref.
Coma	0.0232	4.95	1.5	1
A2199	0.0299	3.2	1.2	3
A85	0.0521	6.65	0.71	2
A3266	0.0545	5.55	0.71	2
A2319	0.0559	4.31	0.70	2
A2256	0.0581	5.4	1.2	3
A1795	0.0621	7.28	0.71	2
A644	0.0704	3.71	0.60	2
A401	0.0748	5.0	1.2	3
A2029	0.0768	5.7	1.2	3
A1650	0.0840	4.17	0.55	2
A478	0.0881	9.05	0.98	2
A2142	0.0899	4.99	0.97	2
A3186	0.1270	6.54	0.75	2
A1413	0.1427	4.07	0.86	2
A545	0.1530	6.40	0.91	2
A2009	0.1530	4.81	0.65	2
A3888	0.1680	4.91	0.56	2
A2218	0.175	6.7	0.4	5
A1689	0.1810	4.84	0.74	2
A665	0.1816	7.00	1.2	2
A1763	0.1870	7.00	0.91	2
A2163	0.2030	5.94	1.1	2
A1246	0.216	7.0	1.3	6
Cl0016+16	0.5545	8.44	1.7	4

The values of M_{gas}/M_{tot} and R are estimated for $\Omega_0 = 0, \lambda_0 = 0$ and $H_0 = 100\mathrm{km\ s^{-1}\ Mpc^{-1}}$. The last column refer to: 1. White et al. (1993). 2. White and Fabian (1995). 3. Buote and Canizares (1996). 4. Neumann and Bohringer (1996). 5. Squires et al. (1996). 6. Kikuchi (1996).

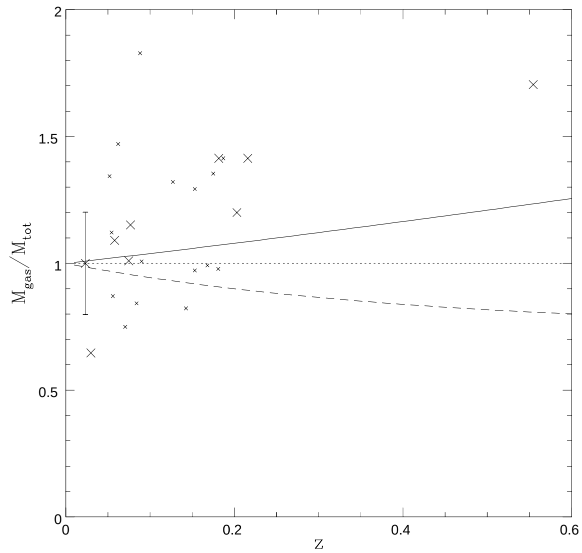

Fig. 2. Same as Fig.1. Crosses are observational data (see table 1) which are normalized by the value of the Coma (which is the leftmost one with error bar). Large crosses indicate clusters with $R > 1h^{-1}$Mpc and small crosses indicate clusters with $R < 1h^{-1}$Mpc. We assume $\Omega_0 = 0$ and $\lambda_0 = 0$.

clusters of galaxies for a range of redshifts. We found that the M_b/M_{tot} vs. z diagram provides information about the values of cosmological parameters if we can determine the baryon fraction within $\sim \pm 10\%$ for a cluster at $z \sim 0.4$. Furthermore, if the baryon fraction of a cluster is identified with the global baryon fraction as in many previous works, we can estimate Ω_b as $\Omega_0 \times (M_b/M_{tot})$ using Ω_0 value derived from the M_b/M_{tot} vs. z diagram. This is a new Ω_b estimation method without using big bang nucleosynthesis studies.

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